Unknown Hydro Unknowns.

(With apologies to Donald Rumsfeld, speech 27 Nov. 2006)

By

J. L. Gordon.

Abstract.

There are many papers on hydro installations, but very few describe any errors or omissions, simply because utilities do not want such incidents publicized. During a career of over 60 years, the author has accumulated details on over almost 50 instances where structures or equipment have not performed as expected. Most incidents have been published in a series of "Lessons learned" columns in the magazine "Hydro Review", where the incident was disguised by changing the numbers slightly. This paper describes four of the more spectacular incidents, a turbine-generator tied down to prevent rotation, with 20,000HP being dissipated through the runner and draft tube (Canada), two exploding turbines (Russia and Nigeria), and one burst new very large concrete casing (Canada).

Index Terms **- Design, Hydro, Construction.**

A PAPER PREPARED FOR PRESENTATION TO

THE CANADIAN SOCIETY FOR SENIOR ENGINEERS – MONTREAL CHAPTER

April 26th, 2012.

1. Introduction.

About 35 years ago, the author was asked to be part of a committee assembled by the Electric Power Research Institute (EPRI) of Palo Alto, California, to promote the interests of a new magazine "Hydro Review" dedicated to hydro in North America. The owner and publisher was an engineer named Carl Vansant, and over the following years the author came to know Carl quite well. We would meet every year at conferences, and discuss the latest hydro gossip. At one of the dinners, Carl mentioned that he had heard rumors of several "incidents", but being an editor, could never obtain any concrete information, and asked me if I knew of any such occurrences. I replied that I had recently written a long paper describing 22 incidents, had submitted the paper to several magazines and journals, but it had always been rejected, with one editor even calling to mention that they would never publish anything negative to hydro. Carl asked for a copy, but then, no word for the next 18 months, and I thought that again, that was the end of it.

However Carl did phone; very excited with an idea. If each "incident" could be enlarged, the accident described in more detail, along with the measures used in the repair, and concluding with a "lesson learned" in a short article of about 1,000 to 1,500 words, he would publish the article in his magazine. Between April 1996 and April 2012, a total of 49 "Lessons Learned" columns were published, and I have received many phone calls from plant operators wanting to know a contact for the plant where the incident had occurred, since he wanted to discuss the details, only to be told – "Joe, that was your plant" – the incident was always disguised by changing numbers and location.

The incidents have ranged from Kaplan turbines installed with the blades upside-down, to penstocks collapsing due to incorrect relief valve controls. It has been a very rewarding and informative experience.

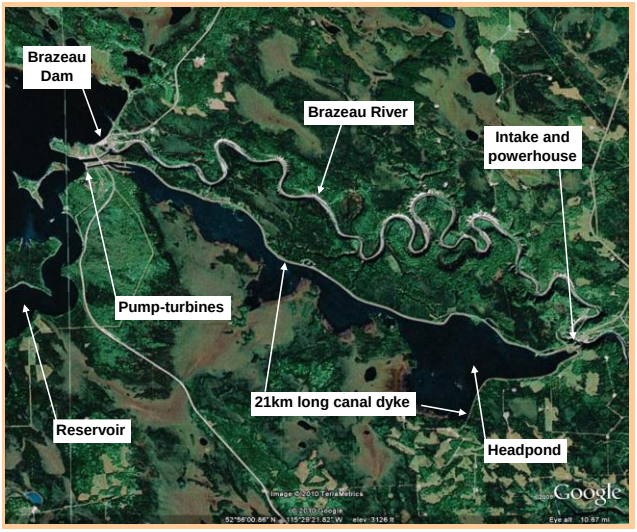
For this dissertation, I have selected four of the more spectacular and interesting "incidents".

2. The Brazeau intake - 1964.

The Brazeau project is quite complex. It includes an embankment dam some 65m high across the Brazeau River, (140km SE of Edmonton) a powerplant containing two unique pump-turbines which pump water up into a long canal when the reservoir is low; and turbine water into the canal when the reservoir is high. Near the downsteam end of the 18km long canal there is a powerhouse with 2 Francis turbines having a total capacity of 343MW. There were two low-level outlets through the dam temporarily used as a spillway, until the main spillway was built several years later between the pump-turbines and the dam.

As consultants on the project, we were encouraged to "push the envelope" on the design, provided we advised the owner, Calgary Power of the risks. Unfortunately in one case, we pushed the design envelope a bit too far.

The intake was founded on over-consolidated glacial till containing discontinuous sand lenses. Our geotechnical consultant was an eminent professor "Dr. Harvey", who had undertaken many design assignments for Calgary Power and was deemed infallible. He had presented his design concept for the intake at a meeting in Montreal attended by the, president of Calgary Power and also of Montreal Engineering, the consulting company, along with several vice-presidents and chief engineers and me. Dr. Harvey and later sent us his report. However, when I saw the report and details of the design for the intake foundation, and water barrier, I was worried about the complexity to such an extent, that I wrote a 2-page memo to Walter, our Chief Civil Engineer and my supervisor, expressing my concerns.



Project layout.

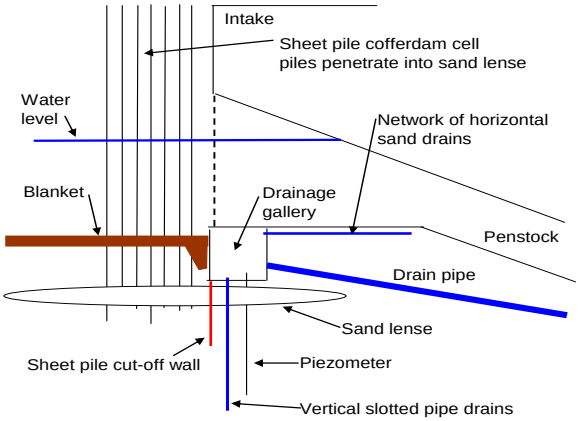
I could not put my finger on exactly what was troubling about the design, other than the fact that the drain below the intake to discharge any seepage, was very large at 18inches diameter. But my instinct said something was definitely wrong. In my memo, which I still have, I discussed the risks in the design and ended by requesting another meeting with Dr. Harvey. My chief civil engineer said I could not question Dr. Harvey's designs, so no meeting and he discarded my memo into the waste paper basket, but I told him I was keeping my copy. However, I was so worried that I requested the site resident engineer, Frank Vassallo, to carefully monitor the water pressure under the intake, a simple task, since there was a drainage gallery below the intake, accessible by a vertical 100ft ladder. I also provided Frank with a chart showing safe, unsafe and disaster uplift water pressures, with a note saying that I had to be advised of the measured pressure on a daily basis.

As the work progressed, all went well. I had been inspecting the construction work about every three months, flying out to Edmonton, renting a car, and driving to the site. The daily pressure readings at the intake showed no

change, and all seemed well. In November 1964, I went to site to commission the first unit, and was met at the airport by a very worried Frank.

View of intake – headpond half full. Vertical inspection shaft is in square box in corner nearest to camera.

He told me that over the past few hours, the water pressure under the intake had started to increase, was now over the safe level, and if it continued at the same rate, it would reach the disaster pressure in just 19 hours. The reservoir in front of the intake was only at half level, a precaution very fortunately proposed by Frank months previously, when he understood my concerns.

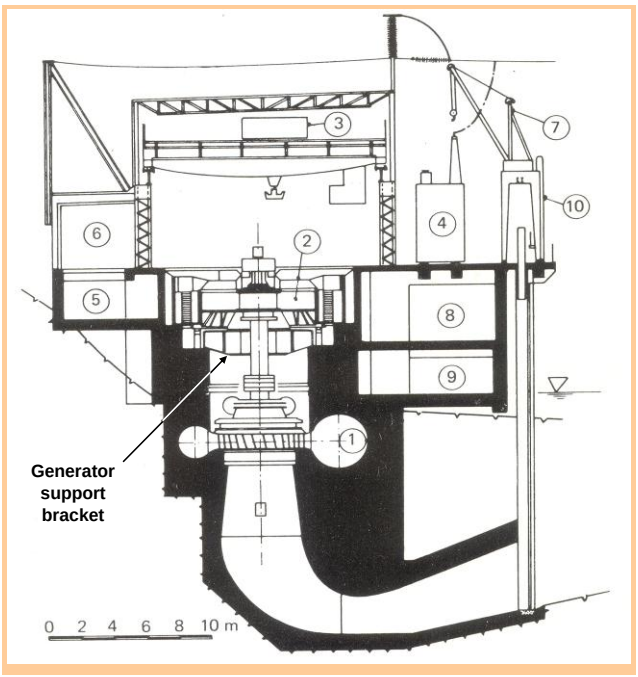


Schematic of intake.

However, there was no way to evacuate the water except through the turbine, unfortunately not ready to operate, since the thrust bearing was still being installed, and this task would not be completed for another few days.

During our discussions on the 90 minute drive back to the site we arrived at a plan to pass water through the turbine by tying down the generator, preventing the unit from rotating, something never done in the past.

At site we had a meeting with the contractor, and the turbine erector Hans Jensen from Dominion Engineering, and phoned Dr. Harvey. We initiated the plan after Frank and I had signed letters taking over control of the project and absolving the contractor and the turbine manufacturer of any damages. The construction camp at the powerhouse was evacuated, and because of the danger, the only staff remaining on site was the contractor's superintendent, Frank and one of his engineers, a volunteer from the survey crew to read the pressure gauges, Bill Maxwell, the plant chief operator, Hans and myself.



Section through Brazeau powerhouse.

Hans, was instructed to stop bearing installation and tie down the 157MW generator by attaching wire ropes from the generator spider to any fixed point in the powerhouse. Within two hours the generator was laced with rope and secure. You almost had to climb through the ropes to access the turbine pit, and I didn't think the generator would rotate under any circumstances, since Hans had done such a good job. The wicket gates were opened to 6% and a close watch was kept on water level in the gallery and flow in the drain at a measuring station between the two penstocks about 80m down the slope from the intake. After about three hours, it became evident that the battle was being lost, and that the wicket gates would have to be opened further.

After some discussion, and over the vociferous objections of Hans, the wicket gates were opened to 11%. By this time the noise and vibration within the powerhouse was indescribable - expected, since something like 20,000 horsepower of energy was being dissipated through the stationary turbine! The effect on the rate of water level rise in the gallery was immediate; it peaked within 0.3m of the gallery roof before subsiding. Within a few more hours the headpond was empty, and the crisis was over.

What had gone wrong? A detailed examination of the headpond upstream of the intake revealed a watertight blanket. However, the rate of water inflow to the gallery indicated that there must have been a direct connection to horizontal sand lenses within the foundation till adjacent to

the intake. Eventually, the investigation concentrated on the sheet steel piles beside the intake, where it was found that there was just enough flow area within the interlocks to conduct water down to the sand lenses, through and below the perimeter sheet steel piling and then up the drains into the gallery. Water could flow into the sheet steel pile interlocks through the vertical steel slots where the steel to steel contact was discontinuous.

The remedial work included welding closed all the vertical interlock slots from 3m below grade to 1m above maximum water level, the addition of a bentonite-beneficiated blanket contact with the sheet steel piling to 3m below grade to improve impermeability, and a float operated alarm in the drainage gallery. The repairs, undertaken in mid-winter, proved successful and operated without incident.

Hans Jensen and Bill Maxwell at powerhouse bridge.

When I returned to Montreal, I walked into Walter's office with my memo. He said to forget about it, and that was the last of the matter, but it certainly was my baptism of fire in the hydro business.

A few years later I was asked to participate in a panel discussion on emergency actions during a dam failure. All the other panel members spoke about committees and action approvals, consultations with the head office and so forth. I asked the chairman if I could speak last, and when I spoke, I summarized the measures taken during the Brazeau failure, without identifying the project, noting the need for immediate actions, sufficient authority to command resources, the ability to take responsibility for the work and someone willing to step in front to direct work without having to refer back to any other offices. This was possible at Brazeau due to the close relationship between consultant and client. It is certainly not possible today with numerous agencies responsible for various safety issues, overlapping jurisdictions, and the inability to assume unquestioned command. This explains the failure of FEMA at New Orleans. Who would be foolish enough today to say to Hans, the turbine erector, "we just have to do it. I will type out a paper absolving Dominion Engineering of all responsibility, you can read it over the phone to Percy Soicher (his superior in Montreal) and we can both sign it".

3. Sayano-Shushenskaya turbine explosion.

Hydro turbines do not explode, but there have been three such incidents worldwide in the past few years, and I have been associated with all three. One was at Grand Rapids in Manitoba, where I was part of a 2-man board, along with Don Coulson, assisting with the investigation. Don managed to find the cause – undersized non-standard bolt heads on the turbine headcover, along with fatigue failure due to improper assembly. The second incident, at Kainji in Nigeria will be described later.

Sayano-Shushenskaya is a large 6,400MW Francis turbine equipped powerplant in Russia, where a turbine exploded at 8.13am on 17th August 2009, unfortunately with considerable loss of life. It is located in south-central Russia, about 280km north of western Mongolia.

Google image of Sayano-Shushenskaya.

There are 10 units with large 650MW turbines, all operating under a rated net head of 194m and at a speed of 142.9rpm. Runner diameter is 6.77m. Total weight of the runner, wicket gate assembly, headcover, shaft and generator rotor is over 1,500tons. Immediately after the explosion, a security camera managed to record the spectacular image of the 1,500 ton spinning turbine and generator suspended on an enormous column of water discharging from the turbine pit for Unit #2, about 10m above the generator floor!

Security camera image of ejected turbine and generator.

When the accident was reported, my first impression was a terrorist act, since the explosion was so catastrophic. However, I was asked to undertake a peer review of an article by Hamill (Ref. 1), from which most of this data has been obtained. The explosion was so severe that it completely destroyed Unit #2, and the

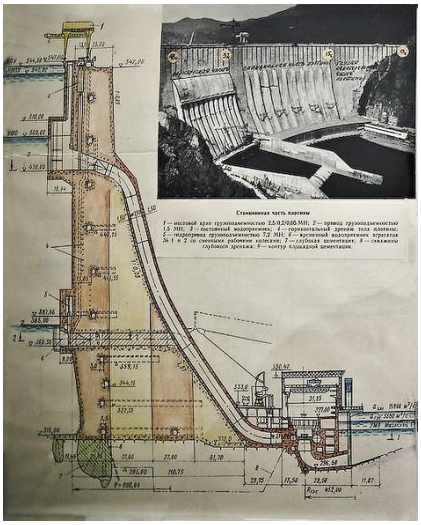
adjacent units. The other units in the powerhouse were also damaged, except Unit #6 which was undergoing repairs. The initial cause of the accident was attributed to fatigue failure of the headcover bolts as at Grand Rapids.

Sayano Shushenskaya before explosion.

Security camera photo of explosion.

Generator floor before explosion.

Generator floor after explosion.



Section through dam and powerhouse

However, the magnitude of the explosion does not support this analysis. Hamill has presented a strong case that the accident was due to draft tube water column separation, and consequent collapse of the vapor bubble exerting an excessive upward force on the turbine headcover, resulting in a catastrophic failure and ejection of the turbine generator from the turbine pit.

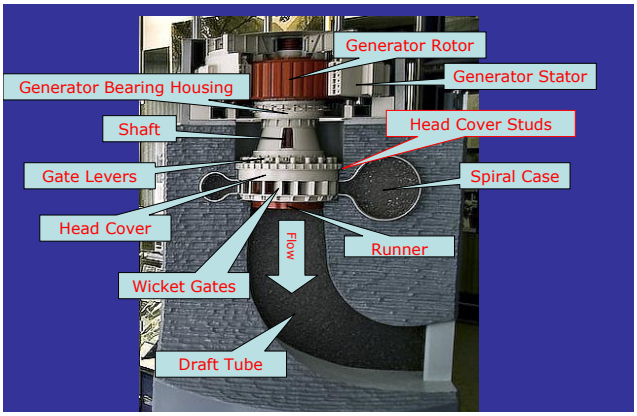
The remains of Unit #2.

The powerplant formed part of the Eastern Siberian grid where 70% of the load was from aluminum smelters. Power was provided by only two plants, Sayano Shushenskaya and the 4,500MW Bratskaya development. Due to the nature of the load, frequency control was very poor. Initially, the Bratskaya powerplant followed the changing load, and Sayano was on base load. However, in 2002, a program to improve frequency control was initiated with the objective of connecting with adjacent power grids, and resulted in the installation of a new automated joint load control along with new governors at Sayano.

Unfortunately, there was a fire at Bratskaya on the day before the accident, and load following requirements were shifted to Sayano. Unit #2 was designated as the lead unit, and experienced large load swings prior to the accident.

At 8.00am, prior to the accident, Unit #2 was operating at near full load, producing 605MW. By 8.13am, the load had been reduced to 475MW, and 25 seconds later, the load was zero.

Damaged powerhouse superstructure.



Section showing turbine-generator components.

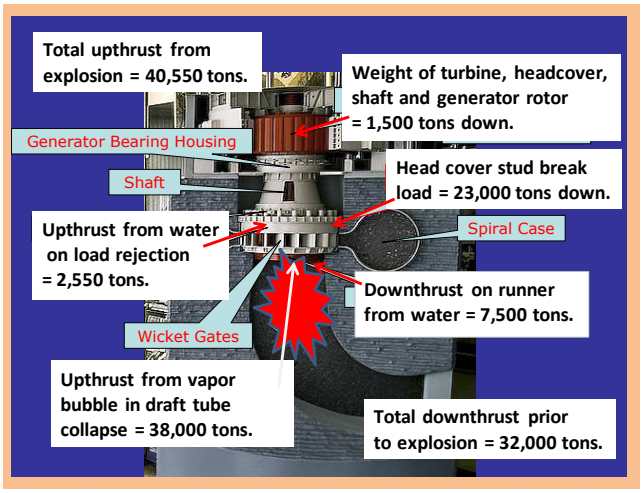
Using published data, Hamill has calculated the forces acting on the turbine runner and head cover just prior to the accident. There were –

- Runner downthrust from hydraulic pressure = 7,500 T.
- Weight down from components = 1,500 Tons.
- Break resistance of headcover studs at ultimate tensile strength = 23,000 Tons.

Total resisting download = 32,000 Tons.

- Waterhammer load up = 2,550 Tons.
- Draft tube vapor cavity collapse causing upthrust on headcover = 38,000 Tons.

Total upward load = 40,550 Tons.


Total upthrust from explosion = 40,550 tons.
Weight of turbine, headcover, shaft and generator rotor = 1,500 tons down.
Generator Bearing Housing
Shaft
Head cover stud break load = 23,000 tons down.
Upthrust from water on load rejection = 2,550 tons.
Spiral Case
Downthrust on runner from water = 7,500 tons.
Wicket Gates
Upthrust from vapor bubble in draft tube collapse = 38,000 tons.
Total downthrust prior to explosion = 32,000 tons.

Load analysis for headcover.

The load combination is subject some criticism, since such loads as waterhammer will not occur during the vapor cavity collapse. Nevertheless, no matter how the loads are added, the exploding force greatly exceeds the holding force, resulting in the catastrophic rupture.

If the accident was due to collapse of the draft tube vapor cavity, the last analysis is to determine the governor closing time which could cause the vapor cavity to form. This was calculated at anything faster than 6 seconds, and this rate of closure could easily have been set on the governor servomotor in an attempt to improve frequency control – faster response = less frequency deviation. There are two other facts to support the analysis –

- The headcover studs all show instantaneous rupture, with no bending, indicating straight upward thrust, confirmed by the security camera photo.
- The wicked gates were all bent outwards, indicating a large internal explosion.

No further data has been divulged by the plant operators, hence this analysis remains to be confirmed – but in the author's opinion, it appears to be correct.

4. La Forge #2 cracked concrete casing.

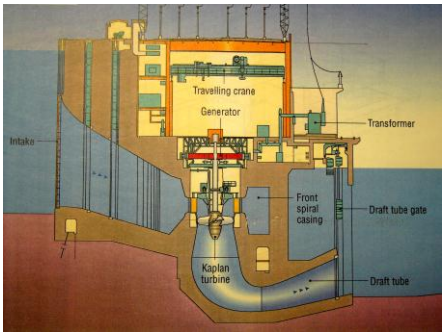
The La Forge #2 powerplant is located in northern Quebec, about 400km west of the entrance to James Bay, and is the most northern powerhouse owned by Hydro Quebec. During September of 1995, the Canadian Electricity Association conducted a tour of the facility as it was nearing completion. I had a good look at the concrete semi-spiral casing, and I was impressed by the size, and had the same reaction when looking at the draft tube! Intake gates are 6.1m wide by 17.75m high. Each turbine produces 155MW at a net head of 28.8m. Flow per unit is 600m^3/s, and the runner diameter is 8.45m.

Aerial view of completed powerhouse and spillway.

However, there was an interesting "incident" during commissioning of the units. The "watering up" process was started wherein the water passages are slowly filled with water through by-pass valves. Due to the large size of the units, this process took many hours, so the commissioning staff decided to let the water flow into the units during the night, expecting to return the next day to continue the commissioning.

Next day they were surprised to hear water running within the powerhouse, and a red light on in the control room indicating an overflow in the sump. They ran downstairs to the turbine floor and were astonished to see

several centimeters of water covering the floor and flooded turbine pits. Closer inspection revealed spouts of water emanating from long cracks in the concrete near the end wall of Unit #2. The by-pass valves were immediately closed, and pumps installed to remove the water. But what had happened?



Section through powerhouse.

A few days later I had a call from Dr. Albert Nessim, an old colleague from Montreal Engineering who asked me a simple question "what is the maximum stress in reinforcing steel where concrete will not crack under the tension?" and I replied that everyone knew the answer – about 83MPa (12,000psi.). Of course, I had to ask why he wanted to know. So he told me about the incident, and that he had photos of the spouting water. I immediately told him that I wanted to see them, since I knew the engineers who had designed the powerhouse, and could not imagine they could make such a mistake in the design. Albert had been engaged to back-engineer the design to determine the cause of the cracking.

The massive concrete structure was so complex, that a finite element computer program had been used to calculate stresses. The concrete beam across the top of the semi-spiral casing was over 6m thick, so there was more than sufficient concrete to take the forces. Albert looked over the program, the modeling shape, and all seemed well.

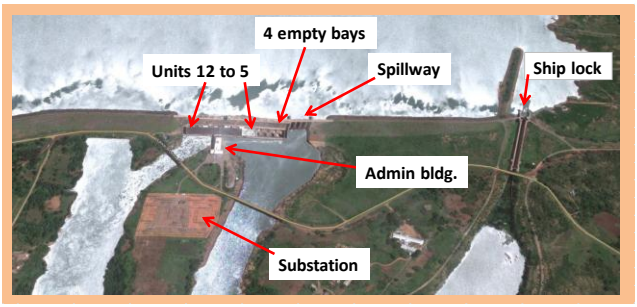
If the program data was correct, the only other source of error was in the boundary conditions. The computer had modeled the surrounding rock with strength parameters for sound granite rock, about 8 times stronger than concrete. The computer output indicated that the rigid rock would act as a vice containing the structure to prevent any movement, resulting in only minimum reinforcing steel being required in the 6m thick concrete slab above the semi-spiral casing. In fact, the rock had been severely cracked when blasting out the excavation for the powerhouse, and was no longer supporting the side walls. The result was cracking due to the water pressure within the casing pushing out the end wall and compressing the cracked rock. By assuming minimum support from the rock, Albert was able to duplicate the crack pattern.

Nineteen post-tensioned anchors were required to stich the structure together and stop the leaks.

This incident shows what can happen when there is a lack of "grey haired what-if" engineers – someone who can ask all sorts of questions about the design assumptions. Fortunately, Hydro-Quebec has taken steps to remedy this.

Inside gigantic La Forge #2 turbine draft tube.

5. Kainji (Nigeria) turbine runaway.



Kainji development.

In 1971, Montreal Engineering obtained a contract to add generation capacity to the Kainji development in central Nigeria. The powerhouse had 4 Kaplan units each generating 85MVA, and 8 empty bays for future units. It was being operated under the supervision of a team from Ontario Hydro, and provided most of the power for Lagos. Over the next 6 years, four more units were installed, 2-115MVA Kaplans, and 2-145MVA propeller units (3). It proved to be a most interesting assignment. In May of 1971, I flew to Lagos and on to the small airport at Kainji, accompanied by two colleagues. We spent most of our time obtaining data for the engineering work, and one morning, when I was in the control room copying some of the operating records, I noted several red lights on the control board. I walked over and saw that they indicated fires at three of the turbine governors.

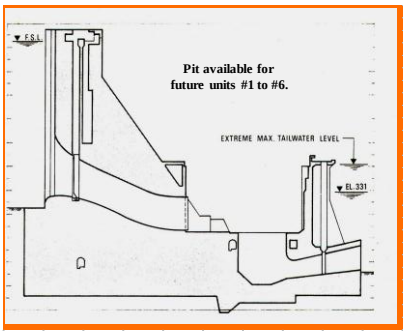
I asked the operator sitting at the control desk why he had not taken any action, and he replied that the red lights were always on. So I walked down to the governors to see what the problem was, and found that the cooling air duct above each governor had been blocked with rags, so the temperature sensor on the governor was above the upper limit, signaling a fire. I then traced the route of the cooling duct back to the upper floor, and found that another vent was in the glass-sided cubicle beside the generator, where the unit operator was stationed. The operator was lying on a

mattress on the floor, fast asleep, with his head beside the vent! I found the same scene in the other three cubicles. I made a note to add some redundancy to the automatic controls for the new units.

Kainji control room. Note red lights.

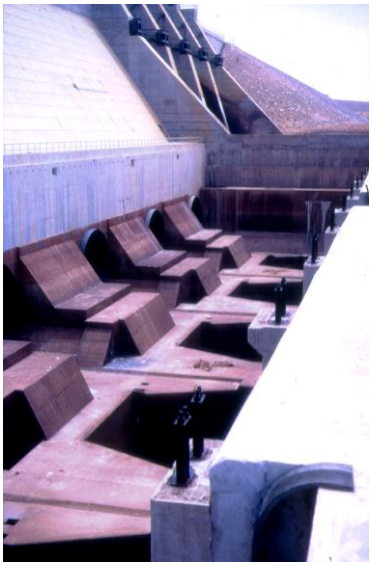
George Cuthbertson, plant operator, Bob Provost and plant manager. Admin building in background.

But we were not successful in designing an absolutely foolproof control system. 30 years later, in 2001, I saw a news item that a turbine unit had "blown up" at Kainji. As mentioned, water turbines just do not explode, so I was curious as to what had happened, and called some of the engineers who had worked on the project. Also, I happened to attend an international conference shortly after; and there was a paper on the incident by an engineer from the United States Bureau of Reclamation (5) who had offered to undertake a free inspection. As is common, the official published report did not fully describe the accident, and I managed to pull together a more accurate description of the event based on the report and my phone calls.



Section through pit for units #1 to #6.

Apparently, the plant operators had great difficulty keeping the equipment operating due to a lack of spare parts, exacerbated by non-convertibility of Nigerian currency and their inability to obtain import permits. Even governor oil was impossible to obtain, and it tended to "disappear" as the operators siphoned off small quantities to be sold in glass vials at the local market as a "personal" lubricant. The result was predictable, low oil in the governor caused an alarm in the control room, and further loss of oil would cause a unit to stop operating, hence all the safety controls, and there were many, were by-passed, allowing the unit to continue operating with no safeguards.



Pit for future units, #5 in bottom foreground.

Eventually the inevitable happened, and the following is an edited extract from the Sadiki paper describing details of the event -

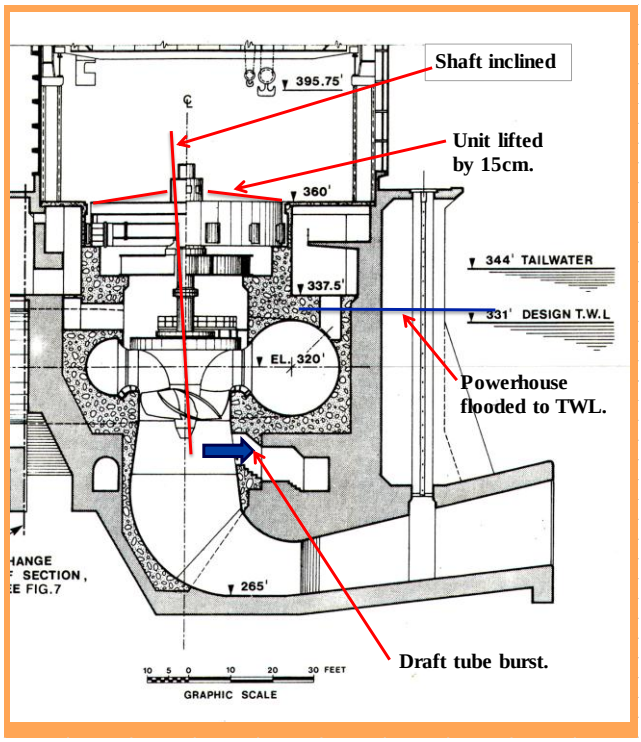
On November 8, 2000, at 10.59GMT, generating Unit #5 lost governor oil pressure. An audible low pressure annunciation was heard in the powerhouse control room and the master relay immediately tripped. The unit rejected 109MW load, tripped a 330kV circuit breaker and immediately started to approach runaway speed. The redundant governor was out of service and there was no backup to close the turbine gates.

At 11.02GMT the turbine was rotating at 50% overspeed. Attempts to control the unit from the Control room and the actuator proved futile. The emergency shut-off switch malfunctioned. (The head-gates were operated with a hydraulic cylinder hoist, and over the years the seals had worn causing the gate to drift down. The limit switch used to keep the gate open had also failed, and was not operational. To prevent the gates closing, they had been propped open with steel beams).

At 11.03GMT, the unit began to vibrate violently off center with extremely loud banging noises caused by the rotor poles crashing against the stator windings, turbine blades hitting the draft tube throat ring and disassembling of the wicket gate linkages. The generator and turbine shaft began to thrust violently up and down in a 1 to 2 second frequency causing tremendous hydraulic pressures. At 11.05GMT a loud explosive noise was heard and the turbine pit started to flood, the (outward opening) *draft tube door failed, and the entire section of the draft tube steel lining was completely blown out.*

At 11.07GMT attempts were made to lower the intake gates. (When the alarm sounded, the chief operator tried to shut down the unit, could not, so he had to close the gates from the top of the dam. He could not take the lift to the dam deck since it had long ago ceased working, and there was no lighting in the stairs, all the light bulbs having been stolen leaving the dark stairway populated by bats and snakes. So he jumped into his car and drove around onto the dam crest, and about 15 minutes after the unit went to over-speed the head gate was almost fully closed, but damage to the turbine was severe).

The unit intake gates were eventually lowered; but a complete seal was not achieved due to damaged seals. Approximately 15m^3/s continued to flow under the gates. Eventually the gates were closed. Flood waters continued to flow (from the open draft tube) *equalizing at tailwater elevation, shutting down the powerhouse for 3 weeks.*



Section through Unit #5, illustrating damage.

The unit has remained out of service until recently, and is now being repaired.

6. Conclusions.

It is only through the publication of such "incidents" that hydro engineers will learn from their mistakes. As mentioned, utilities and consultants, for obvious reasons, are very reluctant to divulge details of incidents. Perhaps, and at the risk of being thrown out of this room, we should encourage a "hydroleaks" website where engineers could post details of incidents, suitably disguised to hide the source and hydro development.

Fortunately, the industry has recognized the need for passing on hydro design and construction experience through the use of "Review Boards" or "Panels of Experts" and now most major hydro developments have such staff on board, reviewing concepts, designs and the ongoing construction work.

References.

1. Hamill, F. A. "Sayano-Shushenskaya accident" Water Power and Dam Construction, Vol. 62, #11, Nov. 2010.
2. Ekolesni. "Reflection on Russian accident on 17 August 2009". Powerpoint presentation obtained from internet. Dated 27 October 2009.
3. Thicke, R. H. And Gordon, J. L. "Turbine selection for the Kainji extension" Trans Eng. Op. Div. CEA 13: 1974, #74-H-105.
4. Gordon, J. L. "Installing Hydro Units in Restricted Spaces", Water Power and Dam Construction 29: 57-62, Dec. 1977.
5. Sadiki, K. "Unit 5 runaway at the Kainji hydropower station: from normal operation to total destruction in 15 minutes! Hydrovision 2002.

Author's biodata.

Jim Gordon graduated from Aberdeen University in 1952 with a first class honors degree in Civil Engineering and commenced work with Montreal Engineering. During this time he was the Chief Design Engineer for 6 hydro projects which received awards "for excellence in design" by the Association of Consulting Engineers of Canada. He has worked in 15 countries, for 9 years he was the Vice-President Hydro, and retired in 1990. Since then, he has practiced as a private consultant, providing advice to consultants and hydro utilities on design, cost, mechanical equipment selection, and has served on many review boards. In 1989, he was awarded the Rickey Gold Medal by the American Society of Civil Engineers, and in 1999, the Distinguished Service Award by the Canadian Electrical Association. In 2010, he was elected as one of "60 most influential people in the industry" that "have helped shape the course of global hydro and dam business over the last 60 years" by readers of International Water Power and Dam Construction. He has authored or co-authored 93 papers, 49 "Lessons learned" articles (in HRW) and been an invited speaker at 32 seminars. Publications are on a large variety of subjects, ranging from submergence at intakes to powerhouse concrete volume, cavitation in turbines, generator inertia and costing of hydropower projects. Also, he authored Chapter 7 "Facilities guidelines and case studies" published in Hydropower Engineering Handbook (McGraw-Hill, 1990). He has developed HydroHelp software program #1 for selection of hydraulic turbines, and HydroHelp #2 to #6 design-cost programs for pre-feasibility assessment of both hydro and hydro pump-turbine projects.